

# STRONGLY-INTERACTING HEAVY FLAVORS BEYOND THE STANDARD MODEL <sup>a</sup>

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The origin of mass must lie in physics beyond the Standard Model. Dynamical electroweak symmetry breaking models like technicolor can generate masses for the  $W$  and  $Z$  bosons. Providing the large top quark mass and large top-bottom mass splitting while keeping  $\Delta\rho$  and flavor-changing neutral currents small requires new strong dynamics for the top and bottom quarks. In consequence, new particles are predicted at scales up to 10 TeV with signatures in jets or heavy flavors. Searches for these states are underway at Fermilab and LEP II.

## 1 Introduction

The cause of electroweak symmetry breaking and the origin of fermion masses remain central concerns of particle theory. The Standard Model, based on the gauge group  $SU(3)_c \times SU(2)_W \times U(1)_Y$  accommodates fermion and weak boson masses by including a fundamental weak doublet of scalar Higgs bosons  $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$  with potential function  $V(\phi) = \lambda \left( \phi^\dagger \phi - \frac{1}{2}v^2 \right)^2$ . However the Standard Model does not explain the dynamics responsible for the generation of mass.

Furthermore, the scalar sector suffers from two serious problems. The scalar mass is unnaturally sensitive to the presence of physics at any higher scale  $\Lambda$  (e.g. the Planck scale), as sketched in figure 1. This is known as the gauge hierarchy problem. In addition, if the scalar must provide a good description of physics up to arbitrarily high scale (i.e., be fundamental), the scalar's self-coupling ( $\lambda$ ) is driven to zero at finite energy scales as indicated in figure 1. But if the scalar field theory is free (or “trivial”), the electroweak symmetry will not spontaneously break! The scalars involved in electroweak symmetry breaking must therefore be composite at some finite energy scale. The Standard Model is only a low-energy effective field theory and the origin of mass lies in physics outside the Standard Model.

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Figure 1: At left, the gauge hierarchy problem:  $M_\phi^2 \propto \Lambda^2$ . At right, triviality:  $\beta(\lambda) = \frac{3\lambda^2}{2\pi^2} > 0$ .

Figure 2: Limits on technihadrons. Left: Projected limits<sup>4</sup> on a color-octet technirho from  $\rho_T \rightarrow jj$  at FNAL. Right: CDF limit<sup>5</sup> on  $\rho_T$  and  $\pi_{LQ}$  masses assuming the leptoquark technipion decays only as  $\pi_{LQ} \rightarrow \tau b$

## 2 Dynamical Symmetry Breaking

In dynamical symmetry breaking theories, the compositeness of the scalar states becomes manifest at scales just above the electroweak scale  $v \sim 250$  GeV. In one realization called technicolor<sup>1</sup>, a new strong gauge interaction with  $\beta < 0$  breaks the chiral symmetries of a set of massless fermions  $T$  at a scale  $\Lambda \sim 1$  TeV. If the fermions carry appropriate electroweak quantum numbers, the resulting condensate  $\langle \bar{T}_L T_R \rangle \neq 0$  breaks the electroweak symmetry. The logarithmic running of the strong gauge coupling renders the low value of the electroweak scale (i.e. the gauge hierarchy) natural. The lack of fundamental scalar bosons obviates concerns about triviality.

The quarks and leptons must couple to the source of electroweak symmetry breaking,  $\langle T\bar{T} \rangle$ , in order to obtain mass. One possibility is to embed technicolor in a larger extended technicolor (ETC) gauge group<sup>2</sup> under which all fermions are charged. When the ETC group breaks to its technicolor subgroup at a scale  $M_{ETC} > \Lambda_{TC}$ , the ETC gauge bosons coupling ordinary fermions  $f$  to technifermions become massive. ETC boson exchange then provides a contact interaction

$$\frac{g_{ETC}^2}{M_{ETC}^2} \bar{f}_L f_R \bar{T}_L T_R \quad (1)$$

which yields a fermion mass  $m_f \sim (g_{ETC}/M_{ETC})^2 (4\pi v^3)$  when the technifermions condense.

Models of dynamical symmetry breaking include many technihadrons for which experiments can search. Their mass scale is set by the electroweak scale, and their role in mass generation requires them to couple to the Standard fermions and electroweak bosons. Recent searches<sup>3</sup> for  $\pi_T$ ,  $\omega_T$  and  $\rho_T$  include many channels  $\rho_T \rightarrow jj$ ;  $\omega_T \rightarrow \gamma\pi_T$ ;  $\rho_T \rightarrow WW$ ,  $W\pi_T$ ,  $\pi_T\pi_T$ ,  $\pi_{LQ}\pi_{LQ}$  [with  $\pi_{LQ} \rightarrow \tau q$ ,  $\nu q$ ;  $\pi_T \rightarrow b\bar{b}$ ,  $c\bar{c}$ ] whose final states involve jets or heavy flavors. Figure 2 illustrates the limits that FNAL searches for resonances decaying to dijets can set on a color-octet technirho<sup>4</sup>. Likewise, searches for leptoquarks<sup>5</sup> constrain a  $\rho_T$  decaying to a pair of technipions ( $\pi_{LQ}$ ) with third-generation leptoquark quantum numbers (figure 2).

These models also confront several key challenges. The large value of  $m_t$  requires a small value for  $M$  – yet data on  $K^0 \bar{K}^0$  mixing imply<sup>2</sup>  $M > 1000$  TeV. Sufficient weak isospin violation must be provided to split  $m_t$  from  $m_b$  – yet weak isospin breaking in technifermion couplings could make  $\Delta\rho$  too large<sup>6</sup>. New strong dynamics for the third family fermions can provide a solution. Suppose that extended technicolor provides only a small mass (and splitting) to the top and bottom quarks and the technifermions at a high scale  $M_{ETC}$ . If new dynamics affecting only  $t$  and  $b$  turns on at a scale  $M$  intermediate between  $M_{ETC}$  and  $\Lambda_{TC}$ , this can provide a large  $m_t$  and  $m_t \gg m_b$  without enlarging the technifermion condensate or mass splittings.

## 3 New Strong Top Dynamics

New strong top quark dynamics is required to provide  $m_t$  in a manner consistent with existing data. This dynamics forms a top quark condensate that will contribute to (cf. topcolor<sup>7</sup>) or even dominate (cf. top mode<sup>8</sup> or top seesaw<sup>9</sup>) electroweak symmetry breaking.

Suppose the top quark feels a color interaction different from that affecting the other up-type quarks<sup>7</sup>. At high energies, the strong gauge interactions would include both an  $SU(3)_h$  for the

$t$  (and  $b$ ) and an  $SU(3)_\ell$  for the other quarks. To be consistent with existing hadronic data, these groups spontaneously break to their diagonal subgroup (identified with  $SU(3)_{QCD}$ ) at a scale  $M$ :  $SU(3)_h \times SU(3)_\ell \rightarrow SU(3)_{QCD}$ . Thus, a color octet of heavy gauge bosons primarily coupled to  $t$  and  $b$  exists at scales below  $M$ . Their exchange yields a new four-fermion interaction

$$-\frac{4\pi\kappa}{M^2} \left( \bar{t} \gamma_\mu \frac{\lambda^a}{2} t \right)^2 \quad (2)$$

that causes top quark condensation<sup>8</sup> ( $\langle \bar{t}t \rangle \neq 0$ ) if the coefficient  $\kappa$  is large enough.

Since these new strong interactions treat the top and bottom quarks identically, one needs a mechanism to prevent the bottom quark from condensing and becoming as massive as the top. One model that accomplishes this goal is the original topcolor-assisted technicolor<sup>7</sup>, which has the following gauge group and symmetry-breaking pattern.

$$\begin{array}{rcl} G_{TC} \times SU(2)_W \times U(1)_h \times U(1)_\ell & \times & SU(3)_h \times SU(3)_\ell \\ & \downarrow & M \geq 1\text{TeV} \\ G_{TC} \times SU(2)_W & \times & U(1)_Y \times SU(3)_C \\ & \downarrow & \Lambda_{TC} \sim 1\text{TeV} \\ U(1)_{EM} & \times & SU(3)_C. \end{array} \quad (3)$$

The groups  $G_{TC}$  and  $SU(2)_W$  are ordinary technicolor and weak interactions; the strong and hypercharge groups labeled “h” couple to 3rd-generation fermions and have stronger couplings than the “ $\ell$ ” groups coupling to light fermions. Each fermion has Standard charges under the groups it couples to. The strong  $U(1)_h$  ensures that the bottom quark will not condense. Below the scale  $M$ , the Lagrangian includes effective interactions for  $\psi_L = (t, b)_L$ ,  $t_R$ , and  $b_R$ :

$$\frac{4\pi\kappa_{tc}}{M^2} \left[ \bar{\psi} \gamma_\mu \frac{\lambda^a}{2} \psi \right]^2 - \frac{4\pi\kappa_1}{M^2} \left[ \frac{1}{3} \bar{\psi}_L \gamma_\mu \psi_L + \frac{4}{3} \bar{t}_R \gamma_\mu t_R - \frac{2}{3} \bar{b}_R \gamma_\mu b_R \right]^2. \quad (4)$$

Only the top quark will condense if the interaction strengths satisfy the relationship<sup>7</sup>:

$$\kappa^t = \kappa_{tc} + \frac{1}{3}\kappa_1 > \kappa_c > \kappa_{tc} - \frac{1}{6}\kappa_1 = \kappa^b, \quad (5)$$

where the critical value is  $\kappa_c \approx 3\pi/8$  in the NJL approximation<sup>10</sup>.

This model combines the strong points of topcolor<sup>7</sup> and extended technicolor<sup>2</sup>, giving a more complete picture of the origin of mass. Technicolor<sup>1</sup> causes most of the electroweak symmetry breaking; the top condensate contributes only a small portion. The  $U(1)_h$  charges of the technifermions can be isospin symmetric to limit contributions to  $\Delta\rho$ . ETC dynamics at a scale  $M \gg 1\text{TeV}$  generates the light fermion masses and contributes about a GeV to the heavy fermions’ masses. Finally, the top condensate provides most of  $m_t$  and the  $t$ - $b$  mass splitting.

## 4 Phenomenology of Strong Top Dynamics

Three classes of models of new strong top dynamics with distinctive spectra are topcolor<sup>7</sup>, flavor-universal extended color<sup>11</sup>, and top seesaw<sup>9</sup>. Exotic particles in these models include colored gauge bosons (topgluons, colorons), color-singlet gauge bosons ( $Z'$ ), composite scalar states (top-pions, q-pions), and heavy fermions (usually, but not always<sup>12</sup>, weak singlets). A search for  $Z' \rightarrow t\bar{t}$  is addressed in ref. 13. Searches for composite scalars are closely related to those for Higgs bosons<sup>13,14</sup>. Here, we focus on new colored gauge bosons and fermions.

Table 1: Fermion strong and hypercharge gauge charges in (a) topcolor and (b) flavor-universal coloron models. Each row refers to a different fermion generation. A charge of “SM” has the same value as in the Standard Model.

(a)	$SU(3)_h$	$SU(3)_\ell$	$U(1)_h$	$U(1)_\ell$	(b)	$SU(3)_h$	$SU(3)_\ell$	$U(1)_h$	$U(1)_\ell$
I	SM	1	0	SM	I	SM	1	0	SM
II	SM	1	0	SM	II	SM	1	0	SM
III	SM	1	SM	0	III	SM	1	SM	0

#### 4.1 Topcolor Models

Topcolor models<sup>7</sup> include an extended  $SU(3)_h \times SU(3)_\ell$  color group and an extended  $U(1)_h \times U(1)_\ell$  hypercharge group; in each case, third generation fermions transform under the stronger “h” group and the other fermions, under the weaker “ $\ell$ ” group (table 1). The weak interactions are Standard. The low-energy spectra of these models typically include a heavy color-octet of gauge bosons called topgluons and a heavy  $Z'$  boson, all primarily coupled to the  $t$  and  $b$  quarks. The new strong interactions affecting  $t$  and  $b$  quarks also form  $t\bar{t}$ ,  $b\bar{b}$  and  $t\bar{b}$  composite scalars.

CDF has looked for signs of  $Z'$  and topgluons in  $b\bar{b}$  final states<sup>15</sup>. Their limit on  $\sigma \cdot BX \rightarrow b\bar{b}$  for a narrow resonance  $X$  falls just short of restricting the mass of a topcolor  $Z'$ . Topgluons, on the other hand, are expected to be quite broad due to their large coupling to quarks. CDF sets limits of  $280 \text{ (340, 640)} < M < 670 \text{ (375, 560)} \text{ GeV}$  on a topgluon with a width equal to 30% (50%, 70%) of its mass. More recently<sup>13</sup> CDF has set a limit on a leptophobic  $Z'$  decaying to  $t\bar{t}$ ; if  $\Gamma(Z') = .012M_{Z'}(.04M_{Z'})$  the bound is  $M_{Z'} > 480 \text{ GeV (780 GeV)}$ . The Run II and LHC experiments will extend these searches in both the  $b\bar{b}$  and  $t\bar{t}$  channels.

#### 4.2 Flavor-Universal Coloron Models

In flavor-universal theories<sup>11</sup> all quarks transform as triplets under only the strong  $SU(3)_h$  group, as in table 1. Hence, in addition to a  $Z'$  boson preferentially coupled to third-generation fermions, these models include a color-octet of coloron bosons that couple equally strongly to all quark flavors. The coloron coupling to quarks is enhanced relative to the QCD interaction strength by a factor of  $\cot \theta \equiv g_h/g_\ell$ . The composite scalars in these models thus include not only the top-pions of topcolor models but also a full range of “q-pions” including quarks of all flavors; this greatly reduces potential contributions to flavor-changing neutral currents.

Limits<sup>16</sup> on flavor-universal colorons are shown in figure 3. Like topgluons, the colorons are generally quite broad. Hence, CDF’s search for new narrow resonances decaying to dijets<sup>4</sup> applies only to relatively weakly-coupling topgluons with small  $\cot \theta$  (cross-hatched region). Light colorons would make noticeable contributions to  $\Delta\rho$  and are excluded in the diagonally hatched region<sup>11</sup>. The shape of the  $D\bar{O}$  dijet angular distribution is sensitive to somewhat heavier colorons, and excludes the light-shaded area<sup>17</sup>. Finally, the shape of the  $D\bar{O}$  dijet mass spectrum places a bound<sup>16</sup>  $M_c/\cot \theta > 837 \text{ GeV}$  on the coloron mass and coupling (dark-shaded region). The horizontally hatched region lies in a different phase of the model<sup>11</sup>.

The strongly-coupled colorons that trigger top quark condensation lie at  $\cot^2 \theta \approx 17$ . The lower bound on their mass is  $\sim 3.4 \text{ TeV}$ , so direct observation of such states must await the LHC.

#### 4.3 Top Seesaw Models

In top seesaw models<sup>9</sup>, only the strong interaction has an extended gauge structure; the weak and hypercharge groups are as in the Standard Model. At a minimum<sup>12</sup>, the third generation of quarks is augmented by a colored weak-singlet state  $\chi$ . The strong and weak charges of the  $t$ ,  $b$  and  $\chi$  quarks are as shown in table 2. Because it is the  $t_l$  and  $\chi_R$  which are triplets under

Table 2: Third-generation fermion charges in a top seesaw model.

	$SU(3)_h$	$SU(3)_\ell$	$SU(2)$
$(t, b)_L$	3	1	2
$t_R, b_R$	1	3	1
$\chi_L$	1	3	1
$\chi_R$	3	1	1

the strong  $SU(3)_h$ , the composite scalar that contributes to electroweak symmetry breaking and  $m_t$  is made of  $\bar{t}_L \chi_R$  rather than  $t\bar{t}$  as in topcolor models. Hence the top quark acquires mass through a seesaw mechanism which indirectly links  $t_L$  with  $t_R$  through the intervening  $\chi$  states:

$$\begin{array}{c} \bar{t}_L \quad \chi_R \quad \chi_L \quad t_R \\ \text{---} \times \text{---} \times \text{---} \times \text{---} \end{array} \quad \left( \begin{array}{cc} \bar{t}_L & \bar{\chi}_L \end{array} \right) \left( \begin{array}{cc} 0 & m_{t\chi} \\ \mu_{\chi t} & \mu_{\chi\chi} \end{array} \right) \left( \begin{array}{c} t_R \\ \chi_R \end{array} \right)$$

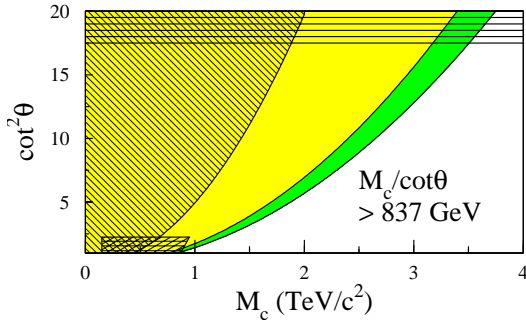
The size of the CDF and DØ top dilepton samples<sup>18</sup> provide a lower bound on the masses of weak-singlet quarks mixing with ordinary quarks. A heavy mass eigenstate ( $q^H$ ) whose left-handed component is mostly weak-singlet could contribute to the dilepton sample via the process  $p\bar{p} \rightarrow q^H \bar{q}^H \rightarrow q^L W \bar{q}^L W \rightarrow q^L \bar{q}^L \ell \nu_{\ell'} \ell' \nu_{\ell'}$ . Note that while  $q^H$  pairs are produced at the same rate as top quark pairs of equal mass, the small weak charge of  $q^H$  suppresses its charged-current branching fraction  $B(q^H \rightarrow q^L W)$ . For  $b^H$ , Cabibbo suppression further inhibits charged-current decays and the flavor-conserving neutral current decay  $B(b^H \rightarrow b^L Z)$  dominates. The CDF and DØ data imply<sup>19</sup> that  $M_{d^H}, s^H \geq 140$  GeV and that (if all quarks have weak-singlet partners)  $M_{b^H} \geq 160$  GeV. Since precision electroweak data indicates that the  $\chi$  states have masses of order several TeV in some models<sup>20</sup>, the direct searches are not yet very restrictive.

## 5 Conclusions

Modern theories of dynamical electroweak symmetry breaking and mass generation include new strong dynamics peculiar to the top and bottom quarks. Hence, these models predict new particles at scales up to 10 TeV with signatures in jets or heavy flavors: technihadrons, topgluons, colorons, exotic quarks,  $Z'$  bosons, and composite scalars. Experiments are already searching for these new states, and there is plenty of room for exciting discoveries at Run II.

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 Figure 3: Experimental limits<sup>16</sup> on the mass and coupling strength of flavor-universal colorons.

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